Single Sideband Optical Signal Generation and Chromatic Dispersion Compensation using Digital Filters

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Single sideband optical signal generation and chromatic dispersion compensation using digital filters

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It is shown that signal processing for single sideband signal generation and electronic chromatic dispersion compensation can be implemented using low complexity digital filters. Effective compensation for the dispersion of up to 1700 km of standard fibre at 10 Gbit/s with 6-bit 20 GSa/s digital sampling was demonstrated.

Introduction: Electronic signal processing techniques are attractive for the compensation of impairments such as chromatic dispersion (CD) in optical fibre communications links since they avoid the use of expensive and bulky optical components. Proposed techniques include decision feedback equalisation [1, 2] and maximum likelihood sequence estimation [3]. However, as phase information is not transferred into the electrical domain after square law detection of double sideband format signals the increase in range that can be obtained using these techniques is limited to a factor of two [4].

An alternative solution which has the potential for greater range is the transmission of single sideband (SSB) optical signals, which results in the optical phase being transferred into the electrical domain, allowing linear electronic filters to be used for compensation [5]. Previous work on SSB has demonstrated compensation of 10 Gbit/s signals using microstrip [5, 6] or SiGe analogue filters [7]. The rapid development of CMOS technology now allows analogue-to-digital conversion at 20 GSa/s [8], enabling cost-effective digital processing of 10 Gbit/s signals. This Letter describes how both SSB drive signal generation in the transmitter and CD compensation in the receiver can be implemented using digital technology. It is shown that compensation for up to 1700 km of standard fibre at 10 Gbit/s can be achieved using only 6-bit 20 GSa/s sampling and low complexity digital filters.

SSB transmitter: The simulated optical SSB transmitter (Fig. 1) used a dual electrode Mach-Zehnder (MZ) modulator driven by signals obtained from a 1024-bit pseudorandom binary sequence (PRBS) generator. To generate the two MZ drive signals, the Hilbert transform of the PRBS digital signal must be obtained. For this purpose, a four-tap digital finite impulse response (FIR) filter was used, with an output given by [5]:

$$\hat{x}(n) = \frac{2}{3\pi}x(n) + \frac{2}{\pi}x(n-2) - \frac{2}{\pi}x(n-4) - \frac{2}{3\pi}x(n-6) \qquad (1)$$

where $x(n)$ is the PRBS sampled at twice the communication bit rate ($2r_b$). The outputs of the 6-bit digital-to-analogue-converters (DAC) were amplified with appropriate bias to produce two drive signals [5]:

$$d_1 = mV_\pi[x+\hat{x}] - \frac{V_\pi}{4} \quad d_2 = mV_\pi[-x+\hat{x}] + \frac{V_\pi}{4} \qquad (2)$$

where V_π is the modulator switching voltage and m controls the extinction ratio. These signals were filtered by lowpass sixth-order Bessel filters, having a 3 dB bandwidth of $0.75r_b$, and applied to the Mach-Zehnder modulator inputs. The electric field of the transmitted SSB signal is then given by [5]:

$$E_{out} = \frac{E_{in}}{2}\exp\left(\frac{j\pi d_1}{V_\pi}\right) + \frac{E_{in}}{2}\exp\left(\frac{j\pi d_2}{V_\pi}\right) \qquad (3)$$

where E_{in} is the output of the CW laser. An optical signal with an extinction ratio of 6 dB was used in all simulations. The low number of Hilbert filter taps and the limited DAC resolution did not significantly impair the overall system performance.

The effect of fibre dispersion was modelled using the transfer function:

$$H(f) = \exp\left(\frac{j\pi DL\lambda^2 f^2}{c}\right) \qquad (4)$$

where D is the fibre dispersion, L is the fibre length, λ is the laser wavelength and f is the frequency offset from the carrier. The effects of fibre nonlinearity and noise were not considered in the simulation.

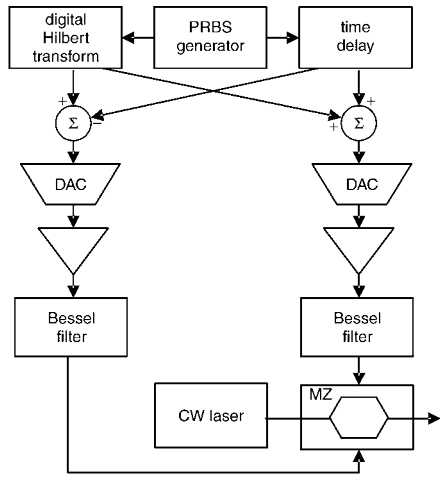

Fig. 1 *SSB transmitter block diagram*

Compensating receiver: The simulated receiver is shown in Fig. 2. After square law detection, the electrical signal was sampled over the full signal magnitude with 6-bit resolution. The sampling and subsequent digital processing were investigated at both r_b and $2r_b$ (i.e. 10 GSa/s and 20 GSa/s for 10 Gbit/s communication). The sampling timing was synchronised to the bit rate and optimised to achieve the best eye opening. The compensating filter was an infinite impulse response (IIR) all-pass digital filter having a group delay response designed to compensate for the effects of CD only (±10% maximum error from ideal compensating response). A commercially available filter design package allowing the use of arbitrary group delay specifications was used. Using sampling at r_b, it was only possible to design the desired response from DC to $0.5r_b$, whereas $2r_b$ sampling allowed a DC to r_b design. However, a lower-order filter was required to produce a good approximation to the desired response with sampling and processing at the bit rate (r_b). In the results presented here, a fifth-order filter was used for the sampling rate r_b and fifteenth-order for $2r_b$. Increasing the filter order above these values to obtain a more accurate fit to the desired response or increasing the ADC resolution produced no significant improvement in overall system performance.

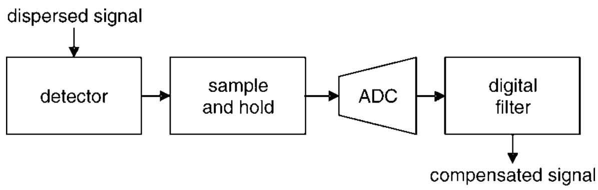

Fig. 2 *Receiver block diagram*

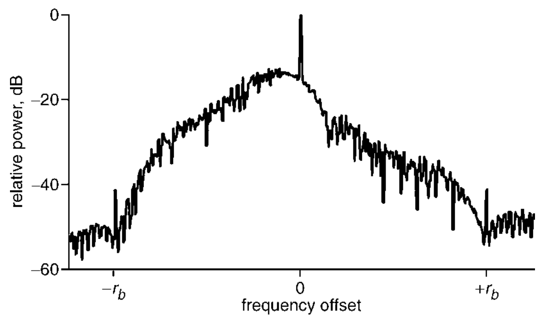

Fig. 3 *SSB transmitted spectrum*

Transmission results: Fig. 3 shows the transmitted SSB spectrum with 84% of the total power in the lower sideband. The vestige of the upper unwanted sideband is retained due to the nonlinear characteristic of the modulator. However, this still allows for a good quality transmitted eye (Fig. 4*a*). Also shown are digital eye diagrams for a 10 Gbit/s link of 640 km standard fibre ($D = 17$ ps/nm · km) compensated using r_b (Fig. 4*c*) and $2r_b$ processing (Fig. 4*d*) compared with the uncompensated analogue eye (Fig. 4*b*). The triangular shape

of the compensated eyes is due to the limited number of sample points per bit period. Fig. 5 shows the eye opening against the length of standard fibre at 10 Gbit/s obtained at both sampling rates. To generalise the results, the product of dispersion, length and bit rate squared (DLr_b^2) is also shown on the x-axis. In the noise-free simulation, compensation for 960 km of standard fibre at 10 Gbit/s was achieved before complete eye closure with sampling and processing at r_b, while over 1700 km, was achieved with $2r_b$. The practical achievable range will depend on the noise performance of the link. For comparison, the uncompensated range for complete eye closure is approximately 150 km at 10 Gbit/s.

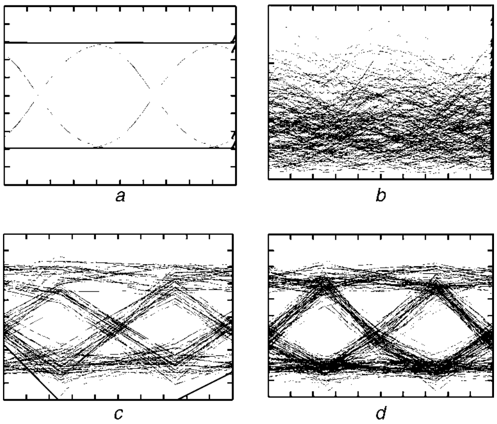

Fig. 4 *Eyes*

a Transmitted analogue SSB eye
b Uncompensated analogue eye at receiver
c Compensated digital eye with r_b
d $2r_b$ processing
5 ps/div.

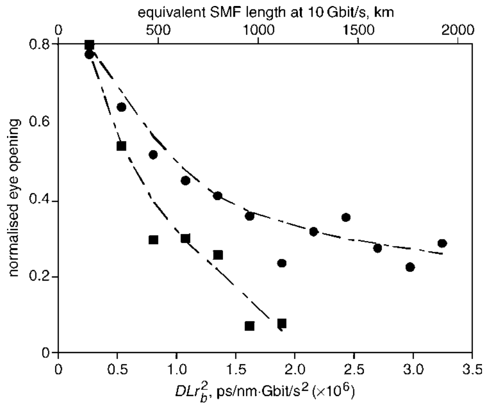

Fig. 5 *Eye opening against 10 Gbit/s standard fibre length and DLr_b^2 for both r_b and $2r_b$ sampling and processing*

■ r_b ● $2r_b$

Conclusions: We have shown that low complexity digital filters can be used for SSB optical signal generation and electronic chromatic dispersion compensation. Good system performance is possible with low DAC and ADC resolutions (6-bit) and low-order digital filters. We demonstrated effective compensation for the dispersion of 1700 km of standard fibre at 10 Gbit/s with sampling at 20 GSa/s. This sample rate is achievable with recently reported CMOS technology [8]. These results demonstrate that the proposed technique can be used to implement cost-effective integrated circuit based adaptive compensation schemes.

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References

1 Otte, S., and Rosenkranz, W.: 'A decision feedback equalizer for dispersion compensation in high speed optical transmission systems'. Int. Conf. on Transparent Optical Networks, ICTON'99, Kieke, Poland, 1999, Paper We.B.2
2 Buchali, F., *et al.*: 'Reduction of the CD penalty at 10 Gb/s by integrated electronic equalisers'. Optical Fiber Communication Conf., OFC 2000, Baltimore, MD, USA, 2000, Paper ThS1
3 Fludger, C.R.S., Whiteaway, J.E.A., and Anslow, P.J.: 'Electronic equalization for low cost 10 Gb/s directly modulated systems'. Optical Fiber Communication Conf., OFC 2004, Los Angeles, CA, USA, 2004, Paper WM7
4 Winters, J.H., and Gitlin, R.D.: 'Electrical signal processing techniques in long-haul fiber-optic systems', *IEEE Trans. Commun.*, 1990, **38**, (9), p. 1439
5 Sieben, M., Conradi, J., and Dodds, D.E.: 'Optical single sideband transmission at 10 Gb/s using only electrical dispersion compensation', *J. Lightwave Technol.*, 1999, **17**, (10), p. 1742
6 Watts, P.M., *et al.*: 'Demonstration of electrical dispersion compensation of single sideband optical transmission'. London Communications Symp., London, UK, 2003, p. 69
7 Bülow, H., Buchali, F., and Nicolas, V.: 'Dispersion mitigation using a fiber-Bragg grating sideband filter and a tunable electronic equalizer'. Optical Fiber Communications Conf., OFC 2001, Anaheim, CA, USA, 2001, Paper WDD34-1, Vol. 3
8 Poulton, K., *et al.*: 'A 20 GS/s 8b ADC with a 1 MB memory in 0.18 µm CMOS'. IEEE Solid State Circuits Conf., San Francisco, CA, USA, 2003, Paper 18.1